Heavy neutrinos masses and mixings at the LHC

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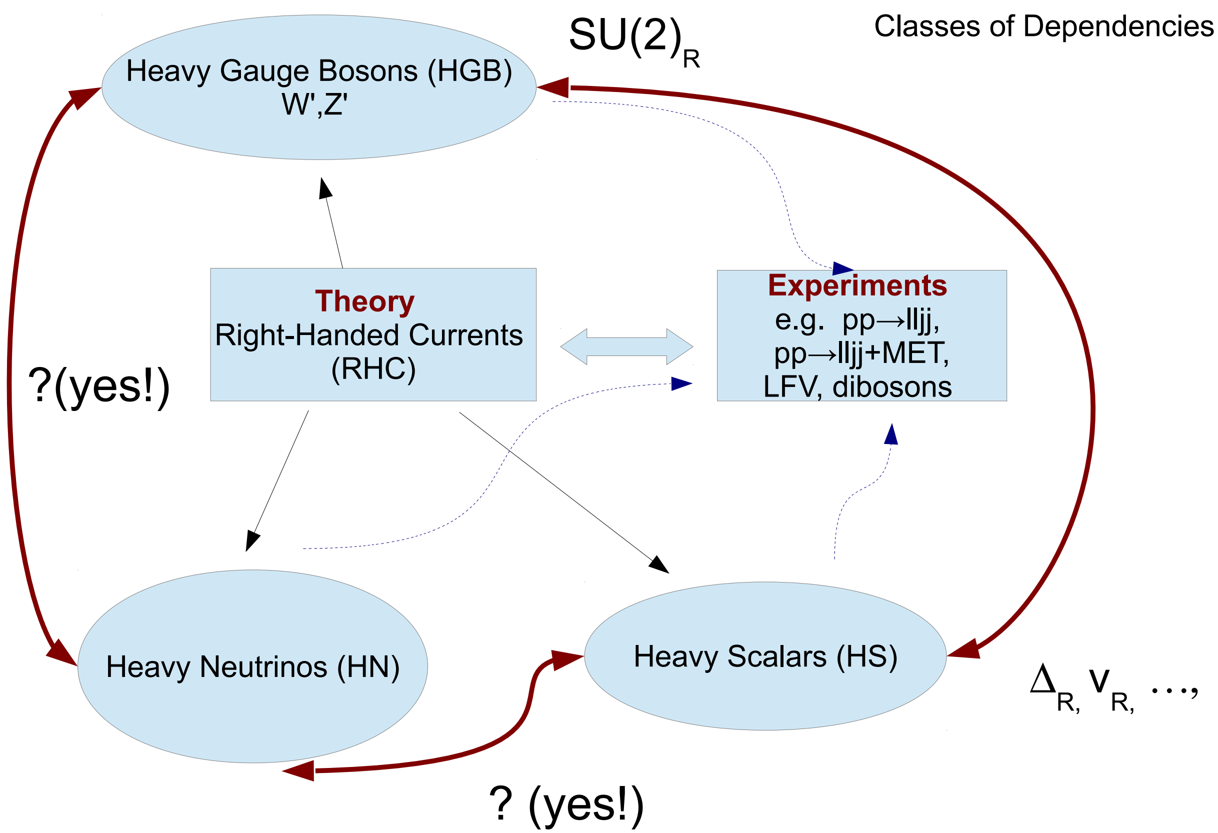
RHC includes plenty of connected issues



LHC-1 excess data

A few deviations from the SM reported by the ATLAS and CMS in invariant mass distributions near 2 TeV:

(i) 3.4σ excess at ∼2 TeV in the ATLAS search interpreted as a W' boson decaying into $WZ \to jj$

(ii) 1.4σ excess at ∼1.9 TeV in the CMS search for jj resonances without distinguishing between the W- and Z-tagged jets

(iii) 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search for a W' and a heavy "right-handed" neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process

(iv) 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$

(v) 2σ excess at ~ 1.8 TeV in the CMS dijet resonance search The ATLAS search in the same channel has yielded only a 1σ excess at 1.8 TeV

Theory vs experiment

Three examples:

(i) "Symmetry Restored in Dibosons at the LHC?" [Brehmer et al., arXiv:1507.00013]

(ii) "Reconciling the 2 TeV Excesses at the LHC in a Linear Seesaw Left-Right Model" [Deppisch et al., arXiv:1508.05940]

(iii) "Unified explanation of the $eejj$, diboson and dijet resonances at the LHC" [Bhupal Dev and Mohapatra, arXiv:1508.02277]

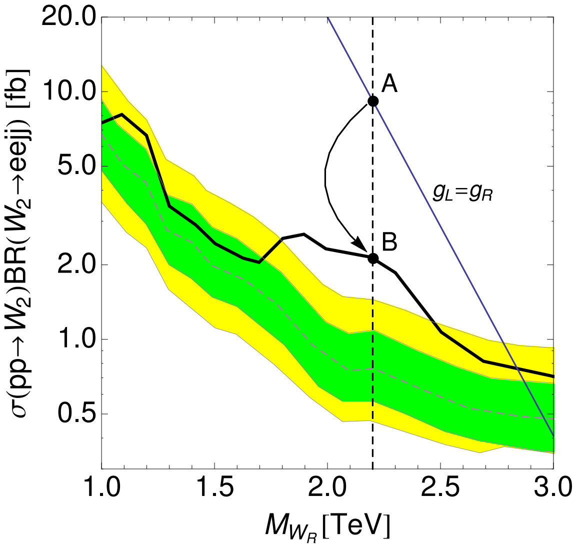
In (ii) linear see-saw is favorable, in (iii) inverse see-saw is favorable over type I see-saw

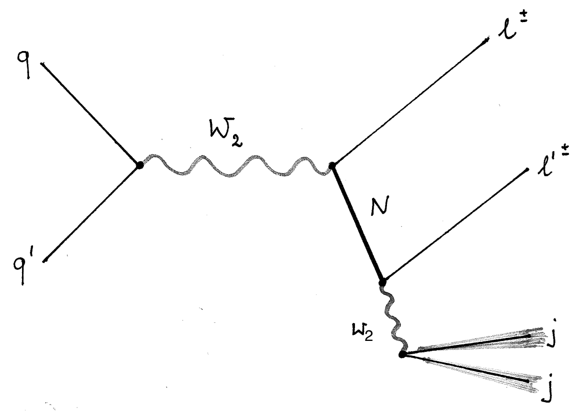
(iv) "Heavy neutrinos and the $pp \to lljj$ CMS data," J. Gluza and T. Jeliński, PLB **748** (2015) 125 [arXiv:1504.05568 [hep-ph]]

Our work:

- Detailed insight into heavy neutrino mass and mixing structures - meaning of interferences

- Nature of neutrinos implies SS and OS content of the dilepton signal





CMS: degenerate neutrinos with trivial mixing matrices, $M_N = M_{W_2}/2$, $g_L = g_R$

ATLAS: even more restricted analysis, comment later on

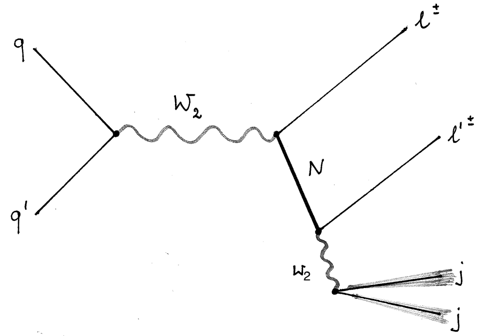
Aim: keep $g_L = g_R$ but go from A to B by exploring heavy neutrino sector

Right-handed currents

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W_{2\mu}^+ + \text{h.c.}$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}, \qquad U \approx \begin{pmatrix} 1 & 0 \\ 0 & K_R^\dagger \end{pmatrix}$$

- heavy gauge boson $W_2^\pm$, $M_{W_2} \sim 2$ TeV
- heavy neutrinos N_a, $M_D \ll M_R$
- K_R is heavy neutrino mixing matrix defined by $M_R = K_R^T \text{diag}(M_{N_1}, M_{N_2}, M_{N_3}) K_R$



CMS data on $pp \to lljj$

1. Ratio of opposite-sign (OS) $pp \to e^{\pm}e^{\mp}jj$ to the same-sign (SS) $pp \to e^{\pm}e^{\pm}jj$ leptons:

$$r_{CMS} = \frac{N_{SS}}{N_{OS}} = \frac{1}{13},$$

2. No excess in the $\mu\mu$ channel
3. Overall excess in $eejj$ production, interpreted by CMS with $g_L = g_R$

$$\gamma = \frac{\sigma(pp \to eejj)_{CMS}}{\sigma(pp \to eejj)_0} \approx 0.54,$$

They can be explained by taking into account N_a mixings!

All the above facts can be reconciled with data if heavy neutrinos with CP phases and mixings are taken into account, e.g.

$$M_{N_{1,3}} = 0.925\,\mathrm{TeV}, \quad M_{N_2} = 10\,\mathrm{TeV}, \quad K_R = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_3}\sin\theta_{13} & 0 & e^{i\phi_3}\cos\theta_{13} \end{pmatrix}$$

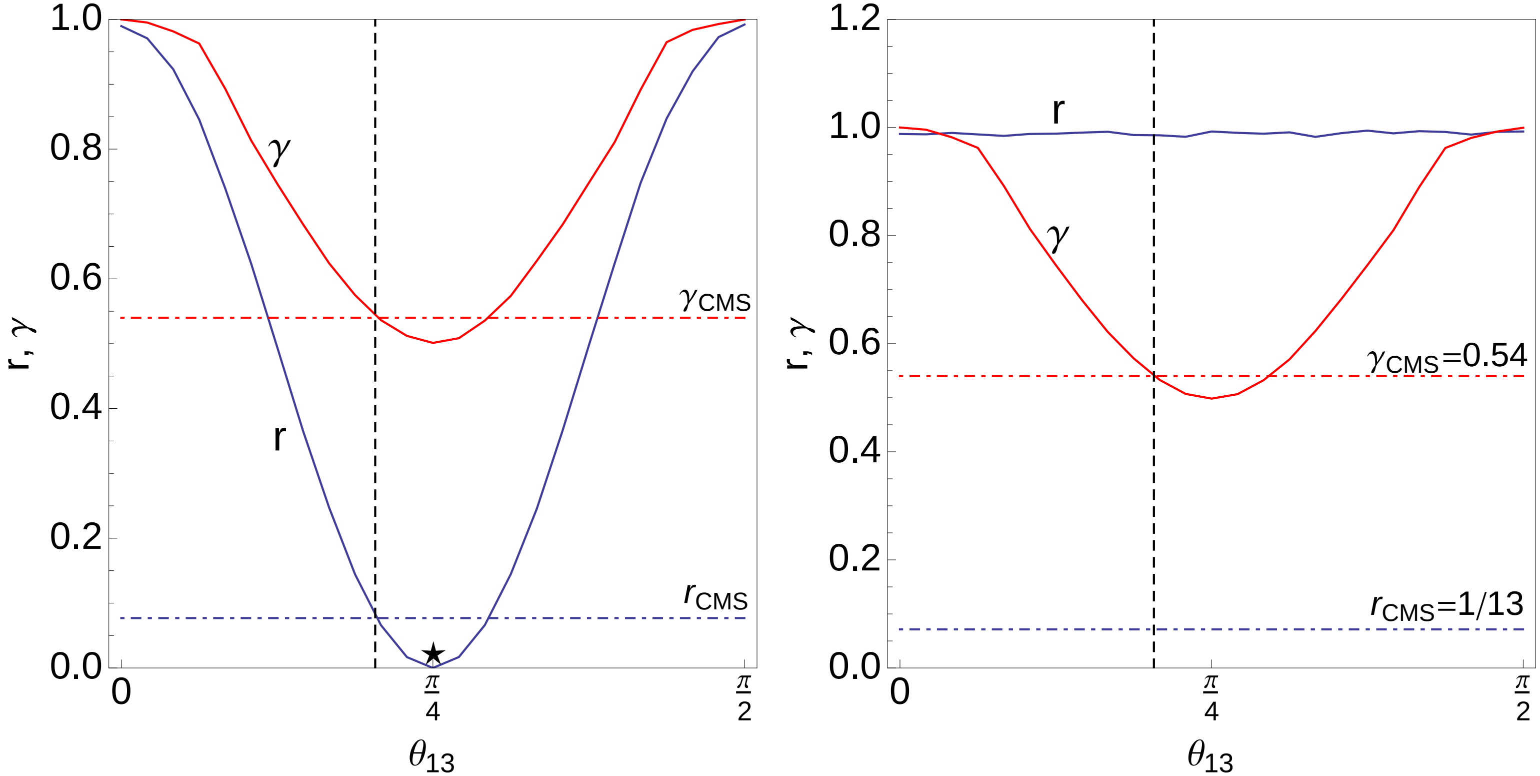
and

$$\sin^2 2\theta_{13} \sin^2\phi_3 = 1 - r_{CMS}.$$

$$\begin{aligned} N_1 &= \cos\theta_{13} N_e + \sin\theta_{13} N_\tau \\ N_2 &= N_\mu \\ N_3 &= -e^{i\phi_3}\sin\theta_{13} N_e + e^{i\phi_3}\cos\theta_{13} N_\tau \end{aligned}$$

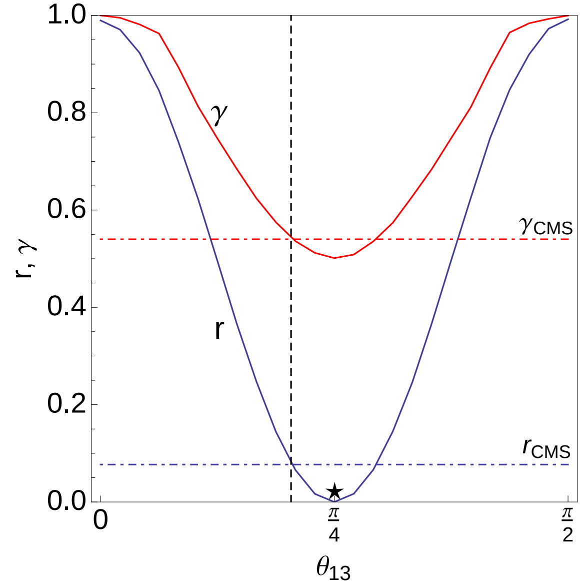
There is no problem with $\mu \to e\gamma$ here.

Effect of mass splitting $\Delta M = M_1 - M_3$ ($\phi_3 = \pi/2$)



$\Delta M \ll \Gamma(N_{1,3})$ $\Delta M \gg \Gamma(N_{1,3})$

Phase-Dirac heavy neutrino



pseudo-Dirac, quasi-Dirac, . . . , phase-Dirac:

$$\Delta M \ll \Gamma(N_{1,3})$$

$$N_1 = \cos\theta_{13} N_e + \sin\theta_{13} N_\tau$$

$$N_3 = -e^{i\phi_3}\sin\theta_{13} N_e + e^{i\phi_3}\cos\theta_{13} N_\tau$$

Remarks on LFV

- For Majorana neutrinos the same number of SS and OS events is expected, while CMS data indicates that $r \ll 1$

Dirac-type of neutrinos must be involved!

- $r \neq 0$ i.e. LFV in $pp \to lljj$ does not necesserarily mean that Majorana neutrinos are there

In fact, lepton number is violated in two cases:

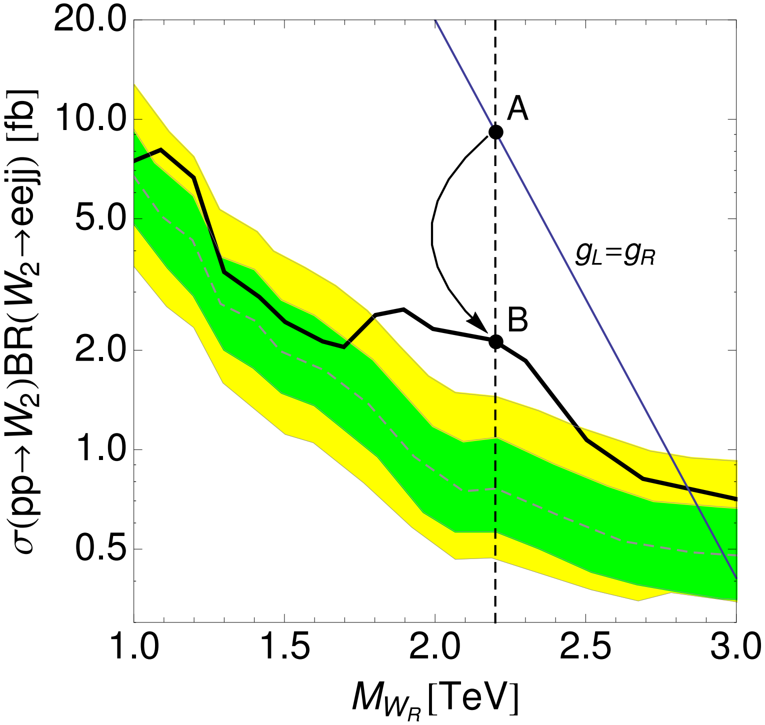
(i) phase-Dirac type of neutrino, compounds of two Majorana degenerate heavy mass states with not maximal mixing and non-trivial CP phase

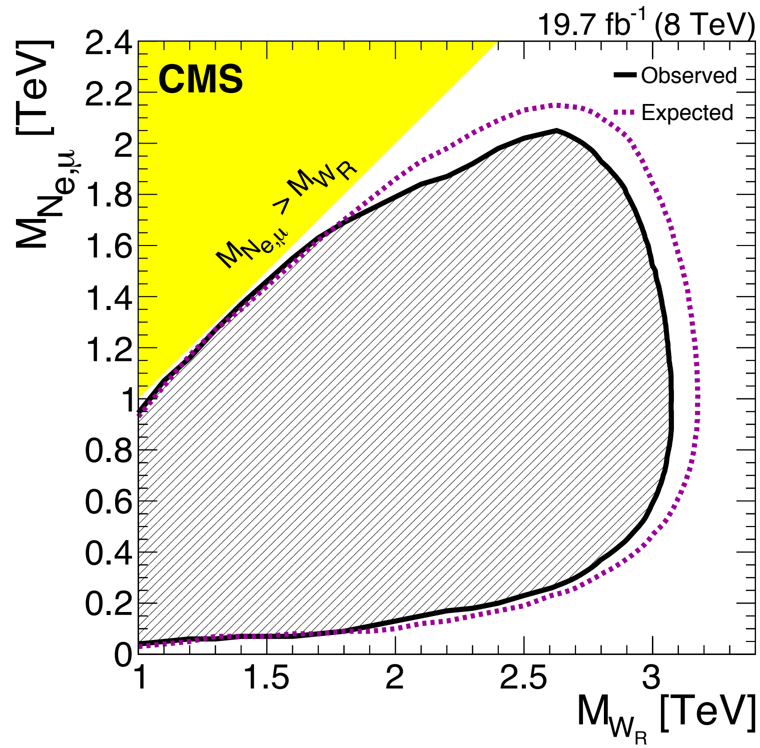
(ii) non-degenerate heavy Majorana mass states

- ATLAS analysis of $pp \to eejj$

  They derive bounds on M_{N_a} looking only for SS events $\to$ possibility that neutrinos are of phase-Dirac is missed!

Remark on exclusion plots





Neglecting heavy neutrino mixings and CP phases seems to lead to oversimplified exclusion plots.

Summary

- details of heavy neutrinos sector are really important for interpreting experimental data

- same-sign events of $pp \to eejj$ are present when heavy neutrinos are of phase-Dirac type